Highly Efficient Amination of Benzene to Aniline Mediated by Bromine with Metal Oxide as Cataloreactant

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We report a highly efficient and versatile two-step process for the amination of benzene to aniline that is mediated by bromine and metal oxides as cataloreactants. The process under mild condition (e.g. below 200 °C) offers an overall yield of ca. 90% and selectivity of ca. 95% for aniline production based on benzene converted.

Aniline ($C_6H_5NH_2$) is an important intermediate for the synthesis of many commodity chemicals in pharmaceutical and chemical industries. Industrially, aniline has mainly been produced by reduction of nitrobenzene ($C_6H_5NO_2$) in the presence of Fe/HCl or fixed bed hydrogenation over a nickel sulfide catalyst.[1] However, such industrial processes suffer drawbacks including high cost of raw materials and difficulty in recycling of catalysts. Alternative to this is the ammonolysis of phenol (C_6H_5OH) and chlorobenzene (C_6H_5Cl) using suitable heterogeneous catalysts.[2] For example, the amination of phenol over modified alumina catalysts has been applied to practical use,[2c,2d] but its cost is higher than that of the reduction of nitrobenzene. In addition to these industrial processes that convert derivatives of benzene into aniline, direct amination of benzene to aniline also has been attempted.[3] These processes displayed either too low conversion of benzene or too low selectivity to aniline to be attractive targets for commercialization. Here, we report a highly efficient and versatile two-step process for the amination of benzene to aniline that is mediated by bromine and metal oxide cataloreactants. The cataloreactants can be readily regenerated upon oxidation of the used ones with no loss of cataloreactivity.

Our synthetic approach is schematically shown in Figure 1. The first step is the bromination of benzene, which produces bromobenzene (C_6H_5Br) and HBr. HBr can be collected with metal oxide or metal hydroxide; further oxidation of the solid mixture gives rise to Br_2 and metal oxide with yields >99%. So there is no loss of bromine and metal oxide in this step. The second step is the ammonolysis of bromobenzene over a metal oxide cataloreactant. In addition to the production of aniline, ammonia-coordinated metal bromide compound is produced, which releases ammonia upon heating. Oxidation of the metal bromide gives rise to Br_2 with regeneration of the metal oxide cataloreactant. So in a cycle, only the raw materials such as ammonia and benzene are consumed, whereas bromine and the metal oxide cataloreactants can be recycled with ideally no loss. This is certainly superior to the Dow process in which the reaction intermediate of copper chloride is not easy for recycle.

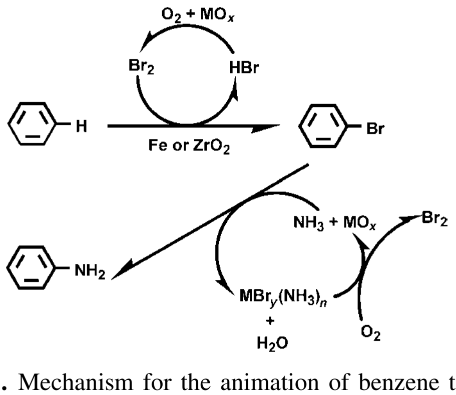

Figure 1. Mechanism for the animation of benzene to aniline mediated by bromine and metal oxide cataloreactants.

The bromination of benzene catalyzed by metal (e.g. Fe or $FeBr_3$) has been well documented. However, in our experiments, we have tested two types of catalysts, i.e., Fe powders and ZrO_2. Gas chromatography analyses of the liquid-phase products from reaction[4] of bromine with excessive benzene catalyzed by Fe powder show that bromobenzene is produced with a yield of ca. 97% and selectivity of >97% based on benzene converted. For the bromination[5] catalyzed by ZrO_2 (pretreated by sulfuric acid), a selectivity of >95% and yield of >95% are obtained for the production of bromobenzene based on benzene consumed.

The ammonolysis of bromobenzene was performed in a stainless steel autoclave with the use of CuO/TiO_2 mixture as cataloreactants.[6] Table 1 lists the conversion of bromobenzene and selectivity of aniline in the reactions of bromobenzene with liquid ammonia over pristine CuO/TiO_2 cataloreactant under different conditions. Under an optimized condition, we obtained a bromobenzene conversion of 97.6% and a selectivity of ca. 95% to aniline, in addition to little amount of benzene (by-product). This corresponds to a yield of ca. 90% for aniline production relative to benzene consumed, indicating that the two-step process concerned is highly efficient for synthesis of aniline from benzene. It is also noteworthy that the ammonolysis of bromobenzene can be completed within 5 h under a much mild

Table 1. Margin specifications

T^a /°C	Quantity of catalo-reactant /g	Quantity of bromo-beneze /mL	Quantity of ammonia /mL	Estimated Pressure^b /atm	Conversion of bromo-benzene /%	Selectivity of aniline /%
180^c	13	10	20	65–80	97.6	94.7
200^d	11	10	20	70–80	87.0	92.0
180^d	13	10	20	57–75	87.4	90.0
200^d	11	10	10	34–37	62.0	69.3

[a]The reactions were carried out at the specified temperature for 4 h. [b]In closed autoclaves, the pressure increases automatically to the estimated range upon heating and gasification of the reactants. [c]Reaction in an autoclave with a Teflon inner wall. [d]Reaction in a stainless steel autoclave.

Table 2. Conversion and product selectivities in the amination of bromobenzene over pristine and regenerated CuO/TiO_2 cataloreactants

Cycle No.	Conversion of bromobenzene	Selectivity of aniline
1	99%	92%
2	100%	90%
3	99%	92%
4	100%	91%
5	100%	92%
6	100%	91%
7	100%	93%

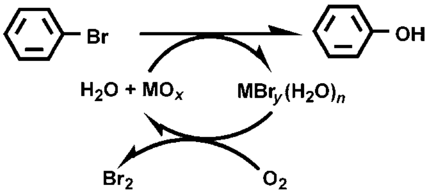

Figure 2. Mechanism for the hydrolysis of bromobenzene to phenol mediated by metal oxide cataloreactants.

condition, i.e., at a temperature of ca. 190 °C, meaning that the energy cost is moderate.

In addition to liquid ammonia, $(NH_4)_2CO_3$ or aqueous ammonia can also be used as amino-source for the amination of bromobenzene with comparable bromobenzene conversion and aniline selectivity, e.g., in the amination of bromobenzene[7] that uses aqueous ammonia as amino-source and pure CuO as cataloreactant, the yield and selectivity to aniline was >95% at a bromobenzene conversion of 100%. Little amount of benzene and phenol were found as by-products.

In catalytic reactions that make use of cataloreactants, of practical important is the regeneration of cataloreactant. This is not problem in the present case. Heating the final products of the ammonolysis of bromobenzene, we obtain separately, ammonia both unreacted and released from the ammonia-coordinated metal bromide, unreacted bromobenzene, benzene, aniline, and solid residue. The solid residue is definitely solid metal bromide. Upon oxidation of the solid residue in a muffle at 350 °C for several hours, we obtained Br_2 and the metal oxide mixture with the yields larger than 99%. Br_2 thus obtained can be reused for the production of bromobenzene, whereas the regenerated metal oxide mixture can be reused in the ammonolysis of bromobenzene. The cataloreactivity of the as-regenerated cataloreactants in a long run has been examined and compared with that of the pristine cataloreactant. Table 2 gives the conversions of bromobenzene and selectivities of anilines in a series of reactions over the pristine and regenerated cataloreactants.[8] It is clear from Table 2 that even after 7 cycles the regenerated cataloreactant displayed slightly higher cataloreactivity than that of the pristine cataloreactant. Hence, we believe the CuO/TiO_2 cataloreactant will keep its cataloreactivity in a long run.

The two-step process shown in Figure 1 can be extended for the synthesis of phenol, another important commodity chemical in industry, by simply modifying the second step, as shown in Figure 2. Using water rather than ammonia, we found that the hydrolysis of bromobenzene affords a phenol yield of ca. 17% at a bromobenzene conversion of ca. 33%.[9] The by-product is benzene that can be recycled for the synthesis of bromobenzene.

It should be emphasized that the two-step process for the synthesis of aniline could be versatile for the production of derivatives of aniline. This target could be readily approached by using various derivatives of benzene, e.g., toluene ($C_6H_5CH_3$), instead of benzene in the first step or using various primary or secondary amines, e.g., methylamine and dimethylamine, instead of ammonia in the second step. The high efficiency, simplicity, and versatility of such a two-step process for the production of aniline (or its derivatives) from benzene (or its derivatives) offer its readiness and overwhelming attractiveness for commercialization.

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4 Typical reaction was carried out in 20 mL of benzene mixed with 0.5 g of Fe powder and 4 mL of Br_2 at 60 °C for 4 h.

5 Typical reaction was carried out in 20 mL of benzene mixed with 0.5 g of ZrO_2 (pretreated with sulfuric acid) and 4 mL of Br_2 at 105 °C for 4 h.

6 The CuO/TiO_2 cataloreactant was prepared as follows. 75.6 g of oxalic acid was dissolved in 300 mL of water. The solution was heated to 60 °C with slow addition of 68 mL of $Ti(OC_4H_9)_4$. A transparent solution (designated as Ti-sol) was obtained and diluted to 400 mL with water. In a separate flask, 40 mL of polyacrylic acid (30%) solution was mixed with ca. 20 mL of $Cu(NO_3)_2$ solution (12 g of $Cu(NO_3)_2 \cdot H_2O$ + 20 mL of water). Upon addition of 100 mL of Ti-sol into the mixture, an aqua-colored colloid was obtained and heated at 110 °C for 5 h. The colloid was dried and calcinated at 500 °C for several hours, giving rise to a dry, sage green solid of CuO/TiO_2.

7 Typical reaction in an autoclave (100 mL) with a Teflon inner wall was carried out using 5 mL of bromobenzene, 5 mL of aqueous ammonia (20% NH_3) and 6 g of CuO at 190 °C for 3 h. The estimated pressure in the autoclave is ca. 17 atm during the reaction.

8 Reactions were carried out at 210 °C for 4 h in stainless steel autoclaves (2.5 mL) fed with 0.45 g of $(NH_4)_2CO_3$, 0.25 mL of bromobenzene, and 0.25 g of pristine or regenerated CuO/TiO_2.

9 Typical reaction was carried out at 240 °C for 4 h in a stainless steel autoclave (2.5 mL) fed with 1.0 mL of water, 0.3 mL of bromobenzene, and 0.5 g of pristine CuO/TiO_2.